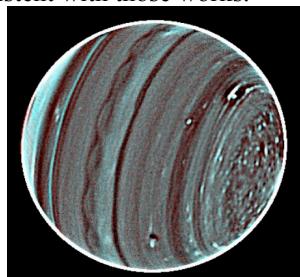


**A VISION FOR ICE GIANT EXPLORATION.** M. Hofstadter<sup>1</sup>, A. Simon<sup>2</sup>, S. Atreya<sup>3</sup>, D. Banfield<sup>4</sup>, J. Fortney<sup>5</sup>, A. Hayes<sup>4</sup>, M. Hedman<sup>6</sup>, G. Hoppel<sup>7</sup>, K. Mandt<sup>8</sup>, A. Masters<sup>9</sup>, M. Showalter<sup>10</sup>, K. Soderlund<sup>11</sup>, D. Turrini<sup>12</sup>, E. P. Turtle<sup>13</sup>, J. Elliott<sup>1</sup>, and K. Reh<sup>1</sup>, <sup>1</sup>Jet Propulsion Laboratory/Caltech (4800 Oak Grove Drive, Pasadena, CA 91109 mark.hofstadter@jpl.nasa.gov), <sup>2</sup>Goddard Space Flight Center, <sup>3</sup>University of Michigan Ann Arbor, <sup>4</sup>Cornell University, <sup>5</sup>University of California Santa Cruz, <sup>6</sup>University of Idaho, <sup>7</sup>University of Iowa, <sup>8</sup>Southwest Research Institute, <sup>9</sup>Imperial College London UK, <sup>10</sup>SETI Institute, <sup>11</sup>University of Texas Austin, <sup>12</sup>Institute for Space Astrophysics and Planetary Rome Italy, <sup>13</sup>Johns Hopkins Applied Physics Lab.

**From Voyager to a Vision for 2050:** NASA and ESA have just completed a study of candidate missions to Uranus and Neptune, the so-called ice giant planets. It is a "Pre-Decadal Survey Study," meant to inform the next Planetary Science Decadal Survey about opportunities for missions launching in the 2020's and early 2030's. There have been no space flight missions to the ice giants since the Voyager 2 flybys of Uranus in 1986 and Neptune in 1989. This paper presents some conclusions of that study (hereafter referred to as The Study), and how the results feed into a vision for where planetary science can be in 2050. Reaching that vision will require investments in technology and ground-based science in the 2020's, flight during the 2030's along with continued technological development of both ground- and space-based capabilities, and data analysis and additional flights in the 2040's.

We first discuss why exploring the ice giants is important. We then summarize the science objectives identified by The Study, and our vision of the science goals for 2050. We then review some of the technologies needed to make this vision a reality.

**The Importance of Ice Giants:** The ice giants Uranus and Neptune, and their rings, satellites, and magnetospheres, are dynamic systems that challenge our understanding of the origins and workings of planets. The current state of knowledge of these systems along with exploration priorities and strategies were summarized in the 2011 Planetary Science Decadal Survey [1] and later workshops [2]. Results of The Study are consistent with those works.



*Fig. 1: Ground-based image of Uranus [3], showing zonal banding, unusual cloud features over the North Pole (right), a high-altitude haze over the South Pole (left), and atmospheric waves creating scalloped clouds near the Equator.*

The ice giants are distinctly different planets from the more familiar gas giants (Jupiter and Saturn) and the terrestrial planets. The terrestrial planets are, by mass, almost entirely made up of "rock", the most refractory elements. Conversely, the gas giants are composed almost entirely of the most volatile elements, hydrogen and helium. Uranus and Neptune contain some rock and gas, but about 2/3 of their mass is species such as water and methane [4], species referred to as "ices". We have not yet carried out a detailed exploration of either ice giant system, leaving significant holes in our understanding of planetary formation and evolution and the history of our solar system. This gap also affects our understanding of exoplanets; the majority of planets discovered around other stars are thought to be ice giants [5], and they are far more abundant in our galaxy than one would think based on our own solar system. The 2011 Decadal Survey [1] recognized the importance of Uranus and Neptune, and called for exploration of an ice giant system with a Flagship mission. Budget realities have pushed that goal into the decades covered by the Visions 2050 workshop. A program of ice giant exploration is central to achieving goals related to the Origins, Workings, and Life themes identified for this workshop.

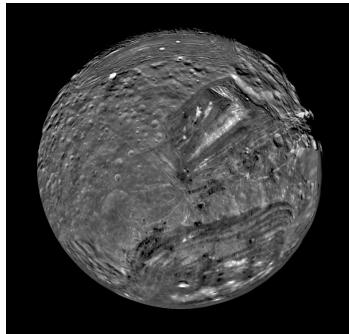
**Science Goals:** This section discusses how the concrete objectives of an ice giant mission launched around 2030 feed into visionary goals for 2050.

*The 2016 Pre-Decadal Study.* At the time of this writing, the final report for NASA's just completed ice-giant study is being assembled. The results will be available in early 2017 at

[http://www.lpi.usra.edu/icegiants/mission\\_study/](http://www.lpi.usra.edu/icegiants/mission_study/).

The highest-priority science objectives identified by The Study target the internal structure and bulk composition (including noble gases and isotopic ratios) of the ice giants. These are the fundamental properties that define what an ice giant is, and constrain models of their formation and evolution. The Study science team identifies 10 additional objectives, all given equal priority, to advance our understanding of the magnetic fields and magnetospheres, satellites, rings, and atmospheric dynamics of the ice giants (see the study report for details and references). These objectives include:

- Understanding the flow of energy and mass from the solar wind into the magnetospheres and upper atmospheres of these planets, utilizing the unique geometries created by their complex magnetic fields which can open and close to the solar wind on 16-hour time scales,
- Determining the geology, composition, and internal structure of Uranus' major satellites, such as the tortured surface of Miranda (Fig. 2), and of Neptune's captured Kuiper Belt Object, Triton,
- Exploring the narrow, dense rings of Uranus and the clumpy rings of Neptune, each displaying features not seen in the broad rings of Saturn or the tenuous rings of Jupiter,
- Exploring the chaotic gravitational interplay of the rings and small moons of Uranus,
- Exploring the nature and driving forces of atmospheric dynamics, Uranus being the only giant planet whose atmospheric energy balance is dominated by sunlight, while Neptune's is dominated—more so than any other giant planet—by the release of internal heat.



*Fig. 2: Miranda, as seen by Voyager 2.*

The Study concludes that Uranus and Neptune are equally valuable and that each is compelling as a scientific target. While equal, however, they are not equivalent. Each planet teaches us different things, and there is tremendous value in visiting both Uranus and Neptune.

*Goals for 2050.* The science objectives just described feed into higher-level goals for 2050.

Specific to the "Origins" theme of this workshop, one science goal is to collect measurements to definitively determine whether planetary migration has occurred. The ice giants have potentially migrated the farthest radially [6], and may contain the most obvious clues in their compositions or in the compositions of their satellites. Another Origins goal is to understand ice-giant formation well enough to be able to reliably infer the composition and structure of exoplanets using only knowledge of their mass, radius, and perhaps the abundance of trace species in their upper atmospheres.

This will allow us to explore the formation and evolution of individual exoplanetary systems.

Regarding the "Workings" theme, exploration of the ice giants is a crucial piece for understanding atmospheric dynamics and the processes that drive them; deep interior dynamics and how they generate magnetic fields; the physics of cataclysmic, stochastic processes such as those that resulted in Uranus' tilt and the expulsion or destruction (presumably by Triton) of Neptune's native large satellites; and mass and energy transport from the solar wind, through a magnetosphere, and into upper atmospheres. The diverse surface geology of the satellites provide information about how cratering, tectonic and cryovolcanic processes can operate at low temperatures, and the dynamical interactions between rings, moons and the planet can place constraints on the lifetime of tightly-packed rings and dynamical systems, and even the internal structures of the planets.

Finally, regarding the "Life" theme of this workshop, we note that each giant planet in our solar system is a potential host of a habitable ocean world, and Uranus and Neptune may contain unique niches for life in their icy satellites and possibly within the extensive oceans thought to exist within the planets themselves.

**Enabling Technologies:** Addressing these science priorities will require technological advances as well as investments in Earth-based observations, modeling, and infrastructure. Technologies discussed in the course of The Study include extremely deep atmospheric probes (to 100's of kbar pressures), multiple long-lived platforms in hydrogen atmospheres, constellations of satellites in the outer solar system, and icy-satellite landers whose design is robust enough to operate in an environment not known at launch. Communication facilities capable of handling large data volumes from the outer solar system are important. Another key component will be rapid and inexpensive access to the outer solar system. Waiting decades for the opportunity to apply the knowledge gained from current discoveries hinders progress and innovation.

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